Minimal climatic control on erosion rates in the Sierra Nevada, California

Clifford S. Riebe*
James W. Kirchner
Department of Earth and Planetary Science, University of California, Berkeley, California 94720-4767, USA
Darryl E. Granger
Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, Indiana 47907, USA
Robert C. Finkel
Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory, Livermore, California 94551, USA

ABSTRACT

Climate is widely thought to regulate erosion rates, but the relationships among precipitation, temperature, and erosion rate have remained speculative, because long-term erosion rates have been difficult to measure. We used cosmogenic nuclides to measure long-term erosion rates at climatically diverse sites in the Sierra Nevada, California, spanning 20–180 cm/yr in annual precipitation and 4–15 °C in mean annual temperature. Average erosion rates vary by only 2.5 fold across these sites and are not correlated with climate, indicating that climate only weakly regulates nonglacial erosion rates in mountainous granitic terrain.

Keywords: cosmogenic nuclides, erosion rates, climate.

INTRODUCTION

Erosional processes set the pattern and pace of landscape evolution. Understanding how erosion rates are regulated by factors such as climate, lithology, and tectonics is important for geomorphological modeling and for interpreting sedimentary records. Erosion rates are also important in geochemical modeling, because physical erosion regulates the supply of fresh mineral surfaces for chemical weathering (Stallard and Edmond, 1983), thereby influencing the geochemistry of soils, streams, and, over long time scales, Earth's oceans and atmosphere (Berner et al., 1983). Because silicate weathering is Earth's long-term sink for atmospheric CO_2 (Berner et al., 1983), quantifying erosion rates and determining how they depend on climate are essential for geochemical modeling of long-term climatic change (Raymo et al., 1988; Molnar and England, 1990).

Climate has been widely thought to regulate erosion rates, but its quantitative importance has remained controversial because erosion rates have been difficult to measure. Sediment yields have commonly been used as a proxy for erosion rates, but because they average erosion only over years or decades, they are often dominated by the effects of anthropogenic disturbance (Milliman et al., 1987) and changes in floodplain sediment storage (Trimble, 1977), rather than reflecting the long-term rate of sediment delivery from hillslopes. Moreover, typical sediment yield studies are based on site to site comparisons, in which the erosional effects of climate are confounded by differences in lithology, tectonics, and land use; these differences make it difficult to isolate climatic variation as a causal factor (Walling and Webb, 1983).

For these reasons, sediment yield studies have not led to a clear consensus about how climate affects erosion rates. For example, several early sediment yield studies argued that erosion rates vary by more than 10 fold as a function of precipitation, but disagreed on the form of the functional relationship (Fig. 1A). More recent studies have shown that sediment yields are correlated with runoff and temperature, but have also highlighted the importance of other factors, such as basin area and relief (Milliman and Syvitski, 1992; Summerfield and Hulton, 1994; Hovius, 1998).

Here we use cosmogenic nuclide methods to quantify how climate affects erosion rates across a set of field sites in which other confounding factors are minimized. Our results show that erosion rates vary by only a factor of 2.5 and are not correlated with climate across an 8-fold range in average annual precipitation and a range of 11 °C in mean annual temperature. The erosion rate variation we measured is much smaller than that expected from previous work; this small variation indicates that climate is a weak regulator of erosion rates across our sites.

METHODS

Attenuation of cosmic radiation in matter limits cosmogenic ^{26}Al and ^{10}Be production in quartz to the upper few meters beneath the Earth's surface. The ^{26}Al and ^{10}Be concentrations in quartz grains therefore reveal their near-surface residence times, which can be interpreted as erosion rates for steadily eroding surfaces (Lal, 1991). If hillslope surfaces contribute eroding sediment in proportion to area and erosion rate, and if quartz is uniformly distributed in bedrock, then streams should mix eroded quartz such that the average nuclide concentration in the quartz reflects its contributing area's average erosion rate (Brown et al., 1995; Bierman and Steig, 1996; Granger et al., 1996; Appendix 1[1]).

To quantify the erosional effects of climate, we used cosmogenic nuclides to infer catchment-wide erosion rates at seven climatically diverse sites in the Sierra Nevada, California (Table 1). We chose sites that are all developed in granitic rock, in order to minimize differences in bedrock erodibility, which could confound any relationship between climate and erosion rates. Our sites exhibit no evidence of deep-seated

*E-mail: riebe@seismo.berkeley.edu.

[1]GSA Data Repository item, 2001047, Appendix 1, Cosmogenic nuclide methods and erosion rate data, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or www.geosociety.org/pubs/ft2001.htm.

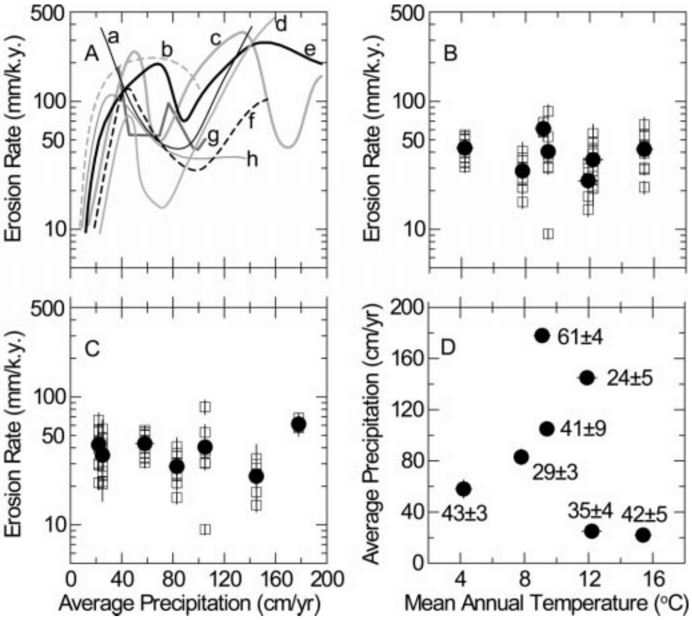

Figure 1. A: Erosion rates (note log scale) as function of average precipitation, and generalized interpretations of sediment yield data from eight studies: a, Fournier (1960); b, Rango (1970); c, Walling and Webb (1983); d, Ohmori (1983); e, Wilson (1973); f, Douglas (1967); g, Langbein and Schumm (1958); h, Judson and Ritter (1964). These studies have led to no clear consensus about how erosion rates vary with precipitation. B–C: Relationships between erosion rates measured by cosmogenic nuclides and average climate indices. Average erosion rates (solid circles) are not correlated with mean annual temperature (B; correlation coefficient = −0.17 ± 0.44, significance level >0.5) or annual average precipitation (C; correlation coefficient = 0.13 ± 0.44, significance level >0.5) and vary only by factor of 2.5 across these sites. Erosion rates of individual catchments (open squares) vary by 2 fold to 8 fold (Table 1) within our sites and are not correlated with either mean annual temperature (B; correlation coefficient = −0.09 ± 0.13, significance level >0.25) or annual average precipitation (C; correlation coefficient = −0.01 ± 0.14, significance level >0.5). D: Average erosion rates (labeled) show no systematic pattern on plot of average precipitation against mean annual temperature.

landsliding or other processes that could preferentially contribute sediment from depths opaque to cosmic rays (and thus complicate our interpretation of cosmogenic nuclide concentrations in stream sediment). Across our seven sites, mean annual temperatures range from 4 to 15 °C (Table 1); this temperature range is twice as large as plausible differences between glacial and interglacial climates (postglacial warming of continents at latitudes <40°N was ~5 °C; Stute et al., 1995). Average annual precipitation varies by 8 fold, from 22 to 178 cm/yr, across our sites (Rantz, 1972); the relationships shown in Figure 1A predict that this precipitation range should correspond to a 5- to 50-fold range in erosion rates. Dominant vegetation also differs markedly from site to site, ranging from desert scrub, to oak woodlands, to conifer forests (Table 1). Large differences in climate imply that erosional processes differ from site to site; for example, sediment transport by tree throw is probably important at forested sites, but unimportant at desert sites, which are instead prone to rainsplash erosion because they lack protective vegetative cover. Our study sites are chosen to minimize differences in lithology and maximize differences in climate, such that each site represents a distinct climatic regime (see Table 1 for site descriptions).

At each site, we sampled sediment from streams and hollows draining several catchments, and then inferred each catchment's erosion rate from the cosmogenic ^{26}Al and ^{10}Be concentrations in the quartz fraction of its sediment. Our catchments are small enough (<112 ha) that the assumption of uniformly distributed quartz should be valid. Because cosmogenic nuclides accumulate in mineral grains over thousands of years, they are unaffected by recent land use (Brown et al., 1998). Long-term erosion rates inferred from cosmogenic nuclides are also insensitive to changes in sediment storage (Granger et al., 1996), particularly in small, steep catchments like ours (average hillslope gradients >0.10; Riebe et al., 2000), where sediment storage area is typically small relative to total catchment area. Therefore, by comparing cosmogenic erosion rate measurements across our sites, we can quantify how erosion rates vary across a diverse array of temperate climatic regimes, without interference from the effects of land use and changes in sediment storage.

RESULTS AND DISCUSSION

Our measurements reveal that site-wide average erosion rates vary by only a factor of 2.5 among our distinct climatic regimes (Table 1; Fig. 1, B–D), much less than the 5-fold to 50-fold variation predicted by prior sediment yield studies (cf. A and C of Fig. 1). Erosion rates vary from catchment to catchment within each site (Table 1), and these intrasite differences are as large (average = factor of 3) as site to site differences in average erosion rates. Erosion rates show no significant correlation with precipitation or temperature, either as site-wide averages or on an individual, catchment-to-catchment basis (Fig. 1, B–D).

TABLE 1. SITE CHARACTERISTICS AND LONG-TERM EROSION RATES

Site	Latitude	Longitude	Intra-site altitude range* (km)	Mean annual temp.† (°C)	Average precip-itation (cm/yr)	Dominant vegetation	Mapped lithology	Cosmogenic erosion rate§		
								Site-wide average (mm/k.y.)	Intra-site range* (mm/k.y.)	n
Nichols Peak	35°37′N	118°13′W	1.12–1.43	15.4 ±0.5	22 ±3	scrub, yucca	Granodiorite	42 ±5	21–66	9
Fort Sage	40°05′N	120°04′W	1.40–1.54	12.2 ±0.6	25 ±3	sage scrub	Tonalite	35 ±4	22–56	11
Adams Peak	39°53′N	120°07′W	1.89–2.25	4.2 ±0.5	58 ±7	mixed conifer	Tonalite	43 ±3	31–55	11
Antelope Lake	40°10′N	120°38′W	1.69–1.80	7.8 ±0.4	83 ±6	mixed conifer	Tonalite	29 ±3	16–41	10
Sunday Peak	35°47′N	118°35′W	2.25–2.42	9.4 ±0.4	105 ±5	mixed conifer	Granite	41 ±9	9–83	6
Fall River	39°38′N	121°16′W	0.87–1.06	11.9 ±0.6	145 ±5	chaparral, oak	Tonalite	24 ±5	14–33	5
Grizzly Dome	39°53′N	121°17′W	1.50–1.51	9.1 ±0.5	178 ±3	oak, conifer	Granodiorite	61 ±4	57–68	4

*Intra-site altitude and erosion rate ranges report minimum and maximum values for individual catchments (number = n) within each site.

†We logged soil temperatures hourly between November 1996 and June 1999. To estimate what mean annual temperatures have been over longer time scales, we first quantified the temperature differences between our sites and nearby weather stations using contemporaneously recorded data, and then used those temperature differences to derive long-term records for our sites from the 40–68-yr-long weather station records. For our Grizzly Dome site, we used a lapse rate of 6 °C/km to derive mean annual temperature from the nearby Fall River site.

§In a separate study (Riebe et al., 2000) we showed that erosion rates are sensitive to tectonic forcing at three of our sites. At these sites, erosion rates increase by up to 15 fold with increasing proximity to fault scarps and river canyons; rapid base-level forcing by faulting and canyon incision has affected erosion rates of proximal catchments but has not yet propagated distally through the drainage network. Because catchment-to-catchment differences in tectonic forcing could obscure any relationships between climate and erosion rates, we limit our analysis here to catchments that are topographically isolated from rapid base-level lowering.

Likewise, the regression slopes (Reed, 1992) relating erosion rates to precipitation and temperature are small and statistically insignificant. These results imply that the effects of climate on erosion rates are too small to be detected in our data, despite the large climatic differences among our sites.

Statistical Power Analysis

How big could the erosional consequences of climate be, yet still remain undetected by our sampling and analysis methods? Statistical power analysis indicates that we would be 90% certain of detecting a statistically significant correlation (at the 5% significance level), if erosion rates changed by more than 17% for each 2 °C rise in temperature, or if erosion rates changed by more than 6% per 10 cm of annual precipitation. These are the largest possible erosional consequences of climate that would be consistent with our data; if the trends were any bigger, we can be 90% certain that we would have detected statistically significant correlations. Thus, the largest plausible climatic effects on erosion rates are much smaller than expected from prior sediment yield studies (e.g., see Fig. 1A).

Late Holocene Climate Fluctuations

Our cosmogenic nuclide data measure erosion rates over thousands of years, whereas our climatic data reflect temperature and precipitation averaged over the past few decades (Rantz, 1972). Do average climates differ enough between these two time scales to substantially confound the analysis presented here? Paleoclimate records for the Sierra Nevada reveal roughly uniform climatic conditions over the past several thousand years. For example, tree-ring records and tree-line reconstructions from bristlecone pine show that, over the past 5500 yr, temperatures have varied by <2 °C in the nearby White Mountains (LaMarche, 1973). Paleosalinity records from San Francisco Bay sediments indicate no overall trend in Sierran river discharge over the past 2700 yr (Ingram et al., 1996). These data indicate that changes in late Holocene climate have been small compared to the 8-fold range in average precipitation and 11 °C range in mean temperature across our sites. Furthermore, late Holocene hydrologic fluctuations were largely synchronous across the western United States (Earle, 1993), implying that they affected the Sierra Nevada as a whole, and therefore would not have substantially altered the site to site climatic differences on which our analysis is based. Thus, the effects of late Holocene climate changes are unlikely to have obscured any strong climatic effects on erosion rates across our sites.

Time Scale of Cosmogenic Averages

Cosmogenic averages are exponentially weighted over time, reflecting erosion during the past few thousand years, rather than erosion predating early Holocene climate shifts. For example, if erosion rates decreased from 50 to 25 mm/k.y. 13 k.y. ago (e.g., due to postglacial climate change), the cosmogenic nuclide concentrations would correspond to an apparent erosion rate of 37 mm/k.y., only 1.5 times faster than erosion rates under the present-day climate (Appendix 1; see footnote 1). Our cosmogenic data should therefore reflect erosion rate patterns imposed by modern climate differences among our sites, even if erosion rates changed significantly due to early Holocene climate shifts.

Pre-Holocene Climate

Although pre-Holocene changes in erosion rates should have minimal effects on our cosmogenic averages, conditions unique to glacial and periglacial settings could still affect cosmogenic nuclide concentrations. For example, shielding by thick ice inhibits nuclide production in eroding rock, and erosion by periglacial mass wasting could deviate significantly from steady state. Either would complicate our interpretation of cosmogenic nuclide concentrations (with both leading to overestimated erosion rates), but our sites were not glaciated during the late Pleistocene or Holocene, and we observe no evidence of periglacial mass wasting at any of the sites (only the highest sites—Adams Peak and Sunday Peak—are likely to have had any permanent snow during recent glacial advances). Thus, it seems unlikely that our cosmogenic erosion rate estimates are strongly affected by pre-Holocene ice and snow shielding or by periglacial activity.

Lithologic Variations

Site to site differences in lithology have been a confounding factor in previous erosion rate studies. However, to obscure (or nullify) a strong systematic relationship between climate and erosion rates among our sites, lithologic effects would have to systematically offset the climatic effects in a way that produced no clear trends. Such a coincidence seems unlikely in our study. Although we cannot completely rule out the possibility of some confounding lithologic effects, even across the similar granites of our sites, such effects could not plausibly produce the patterns of Figure 1 (B–D) if climate were an important regulator of erosion rates. Because lithologic effects and climatic changes are unlikely to have substantially distorted the relationships plotted in Figure 1 (B–D), our data indicate that site to site climatic differences have little effect on long-term sediment production by hillslope erosion across the wide range of climatic regimes represented by our study sites.

Effects of Climate on Sediment Production on Hillslopes

There is little doubt that changes in climate and vegetation influence sediment delivery rates over the short term, particularly in semiarid regions (e.g., Knox, 1983) where sparse vegetation incompletely shields the ground from sediment transport by rainsplash. However, short-term measurements of sediment delivery (e.g., Fig. 1A) do not clearly reveal how climate affects erosion rates, because sediment delivery rates reflect both the rate of sediment production by erosion and any changes in sediment storage (Trimble, 1977). Climate change can alter sediment storage by triggering mobilization or deposition of sediment on flood plains, terraces (Bull, 1964), and colluvial hollows (Reneau et al., 1990), and thus substantially alter short-term rates of sediment delivery. Whether climate change can also alter rates of sediment production, however, has remained uncertain in the absence of long-term measurements like ours. Because our cosmogenic nuclide data are insensitive to changes in sediment storage (Granger et al., 1996), they can be used to directly infer long-term erosion rates and thus shed light on how climate affects rates of sediment production by erosion. Our measurements at the Sierra Nevada sites (Fig. 1, B–D) show that relationships derived from short-term sediment delivery rates (Fig. 1A) would greatly overpredict how long-term hillslope sediment production responds to climate change in mountainous granitic terrain.

IMPLICATIONS

Our results show that nonglacial erosion rates in the Sierra Nevada are insensitive to climate. If this is similarly true in other mountain ranges, it would imply that any climatic changes that are too subtle to induce glaciation will not be substantially dampened or amplified through an erosionally mediated feedback among silicate weathering, atmospheric CO_2, and climate. Nevertheless, such a feedback could be important in regulating interglacial to glacial climate shifts, because glaciers can erode crystalline landscapes ten times faster (Hallet et al., 1996) than the nonglacial erosion rates measured here. Glaciation should substantially accelerate physical erosion, thereby increasing silicate weathering rates, inducing faster CO_2 consumption, and promoting more extensive glacial advances through global cooling (Raymo et al., 1988).

Our results suggest that in the absence of glacial-interglacial transitions, climate shifts may have little effect on rates of erosion and relief production in mountain ranges like the Sierra Nevada. Thus, Sierran peak elevations (Small and Anderson, 1998) and isostatic response to erosional unloading (Montgomery, 1994; Small and Anderson, 1995) will be minimally affected by climate shifts that are too subtle to induce glaciation. Thus, our results suggest that climate shifts may be unable to drive strong feedbacks among surficial and crustal processes, and further suggest that landscapes like the Sierra Nevada should exhibit minimal tectonic response to climatic change if glacial erosion is not induced.

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